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Future perspectives on sustainable tribology

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ABSTRACT

This paper highlights the future perspectives of sustainable tribology by examining the economic, environmental and social impact of three tribological case studies. One case study examines the sustainability and durability of micro-CHP systems looking the tribological phenomena generated within a scroll expander system. The scroll is the main part of a specific micro-CHP system and experiences wear and cavitation damage. The tribological optimization of the scroll expander improves the sustainability of the micro-CHP unit while it has a serious economic and environmental impact to the consumers and to the society in general. Another case study is focused on friction and wear performance of lifeboat launch slipways. The causes of high friction and wear during the RNLI's lifeboat launches along an inclined slipway are investigated with a view to reducing the environmental impact due to slipway panel wear and lubricant release into the marine environment. The project encompasses the sustainable design of slipway panels using design modifications based on tribological investigations to double their lifespan, while environmental and economic impact was significantly reduced by the use of biodegradable greases and water as lubricants. The final case study involves an investigation of recycled plastic materials to replace polyurethane used on skateboard wheels, scooters and similar applications. Polyurethane (PU) is difficult to recycle. With the dwindling resources and environmental problems facing the world today, recycling for both waste reduction and resource preservation has become an increasingly important aspect of sustainability. The tribological results showed that recycled polycarbonate plastic can effectively act as a substitute to polyurethane wheels. Moreover, sustainability considerations showing the environmental benefits of the use of recycled plastics over PU include reducing the CO_2 footprint by 50% and the energy consumed by 60%, among other benefits. These case studies emphasise the importance of sustainable tribology in our epoch showing that increased sustainability performance can be achieved through tribology to a significant extent in many cases, providing stability to our world and more viable long term growth to our societies.

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1. Introduction

Energy constitutes the main motivator for each human activity. Nowadays, energy is deeply embedded in each of the economic, social and environmental dimensions of human development. Energy services provide an essential input to economic activity while they improve living conditions and environmental quality. They also contribute to social development through education and public health, and help meet the basic human needs for food and shelter. However extensive use of energy can increase carbon footprints and greenhouse gas emissions while conversely mismanagement of energy resources can cause harm to existing ecosystems. Thus relationships between energy use and human development are extremely complex.

It is the role of the designer to attempt to bridge this gap between our desire for energy and the adverse environmental effects it produces by designing machines that can still meet society's needs while substantially reducing our dependence on fossil fuels for energy. A prime aspect of this is in reducing the inefficient systemic losses through friction and wear which reduce the performance of these machines. Another approach is to identify the aspects of a technology that have the greatest impact on the eco-system and to try and reduce or eliminate this impact. In recent years increasing realisation of the harmful effects of chlorofluorocarbons (CFCs) as refrigerants, lead in petrol, etc. have led to these substances being eliminated [1,2], while scientists have had to devise substitute materials to maintain the low friction and reliability of the components affected. Thus the designer finds himself under the twin pressures of having to reduce systemic losses and failures, while often simultaneously developing low-impact alternatives to the environmentally damaging lubricant practices already in play.

In order to address the frictional and wear losses, durability and sustainability in the main components of a mechanical system it is necessary to have a clear idea of the engineering science underpinning their operation. This is the science of tribology. Tribology is a compound word which derives from the Greek words 'tribos' and 'logos', meaning rubbing and word respectively. In practice, this means the control and management of friction and wear, wherever it occurs. The word was first used in 1966 in Great Britain by H.P. Jost, chairman of a group of British lubrication engineers, to describe the scientific and technical domains focused on the study of friction, wear and lubrication phenomena. However the word tribology was foreign to many people even to some in science and engineering since the 1990s [3]. The concept of friction and wear has concerned great scientists since the time of Aristotle (384–322 BC) [4]. Leonardo Da Vinci later formulated two empirical laws of friction. Da Vinci found that the friction force is proportional to the normal load and independent of the contact area. To these a third law was added by Coulomb in 1785 stating that friction force is independent to sliding velocity [5]. However the real understanding of wear and friction mechanisms was only achieved with the great developments that followed the industrial revolution in the early 18th century. That period was the turning point of a new era where a bright century was followed with great engineering achievements and grand designs. Unfortunately environmental quality considerations fell into disuse after the industrial revolution, in an era where man believed in his omnipotence and exhausted without measure the resources in the planet. This wasteful use of natural resources and the increasing emission of greenhouse gases lead humanity to the energy crisis in mid 1970s. However through that crisis the new research area of 'sustainable' or 'green' tribology emerged, dealing with the preservation of energy, environmental protection as well as improving quality of life. Nowadays tribology is a wide-ranging multi-disciplinary field of study and research investigating the life-cycle, durability, reliability and efficiency, of every manufactured mechanical system around the globe.

"The benefits of tribology and especially of sustainable tribology have been quantified and enunciated by investigations in several countries, of which the Chinese report may be regarded as the most prominent one" [6]. Si-Wei Zhang's outlined the recent report from the Chinese Academy of Engineering that claimed a 1.1 to 1.5% UK GNP (Gross National Product) saving if tribology was fully engaged in the UK [7]. Additionally the importance of tribology in an international level is shown, after a thorough consideration of the results of an extensive two year investigation in China, involving six industries and conservatively estimated savings of $414 hundred million per annum, at 2006 rates, equivalent to savings in China of 1.55% GDP (Gross Domestic Product) [8]. This investigation shows the clear economic and energy benefits of an extensive and orthological use of sustainable tribology. This echoes the 1966 report made by Jost, where he predicted that UK industry could save 1.5% of GDP (£515 million per annum at 1965 values) through better tribology [9]. However 45 years later only around a tenth of these savings

have been achieved, [10] but even this small percentage shows gigantic energy savings on the large scale. In 1976 in West Germany another report revealed the economic losses caused by friction and wear which are estimated to be around 10 billion Deutsche Mark per annum at 1975 values (5 billion Euros today) which is equivalent to 1% of the GNP [11]. Finally, it has been estimated that approximately 11 percent of the total energy annually consumed in the U.S. in the four major areas of transportation, turbomachinery, power generation and industrial processes can be saved through new developments in lubrication and tribology [12].

The massive potential worldwide of the economic and environmental benefits reveal the importance of tribology in reducing overall global carbon emissions. The key drivers to the technological progress of tribology are subsequently based on sustainability. 'Sustainable' or 'green' tribology can be defined as the science and technology of the tribological aspects of ecological balance and of environmental and biological impacts [13]. Sustainable tribology emphasizes the aspects of interacting surfaces in relative motion, which are of importance for energy or environmental sustainability while aiming to minimise the vast energy losses and effectively manage the economic costs which could be saved by the better use of machines and engineering components. A recent review on the frontiers of fundamental tribological research emphasizes the concern over the environmental issues such as biodegradability in the development of tribo-materials in order that sustainability can be achieved [14]. Additionally, Taylor's research emphasises the importance of tribological design of the major frictional components of automotive internal combustion engines [15]. In 1994 were 500 millions vehicles registered for use globally with an additional 40 to 50 million cars produced in the world every year [16]. A reduction in the mechanical losses due to effective tribology about 10% could lead to a reduction in the fuel consumption of 1.5% equating to about 340 l of petrol during car's lifetime (about 125.000 miles) apart from the environmental gains due to reduced emissions [15]. Thus it becomes clear that if you integrate these small savings ($350) per car to the vast number of cars currently in use the economic savings and environmental benefits are huge. Moreover, Holmberg is focused on the reliability and endurance life of mechanical components by producing more and better tribological data [17]. He suggested that laboratory testing of materials combinations in specific contact situations and environments is today the most reliable way of gaining basic tribological data for reliability control purposes. Glavatskih highlights the importance of a tribotronincs approach to the design of tribotronic systems [18]. He believes that a successful combination of tribological knowledge, electronics, engineering and mechatronics will enable the design tribologist to extend the limit of machine service life, durability and reliability. Furthermore Wood et al. [19] investigate the tribology of renewable sources of energy such as wind and tidal turbines, highlighting the importance of design and durability for these large scale engineering systems in order that the potential of this green energy source is sustained by producing reliable energy. Howarth and Hadfield [20] have generated a model assessing the sustainable development aspects of a product from a design perspective depicting the environmental, social and economic impact. Additionally, chemical methods of analysis are of relevance to the sustainable tribology concept. Li in his paper emphasizes the importance of green waxes, adhesives and lubricants on the technological improvement and materials development thinking environmentally [21]. The use of natural resources in a feasible and economical manner in order to develop suitable raw materials through green chemistry for the new generation of waxes, adhesives and lubricants is one of the greatest challenges of the following years. Finally, Novonsky discusses the concept of entropy in various dissipative friction and wear processes such as adhesion, chemical reaction, phase transition, etc. [22]. The relation between structure parameters and entropy is determined while the importance of self-organization effects in tribo-systems is designated. Novonsky has shown that the entropic methods are important for the investigation of the fundamental problems related to friction and wear and the design of new materials. Finally, Nosonovsky and Bhushan examined various biological surfaces of biomimetic organisms created by the evolution of having special tribological properties and hierarchical structure, addressing the different physical mechanisms contributing to friction, hence the friction mechanisms can be better controlled optimizing the frictional losses of many industrial applications [23]. Thus, from all the aforementioned studies it can be comprehended that under the umbrella of tribology a compilation of different scientific fields are well linked together embracing sustainable development and life quality. Nosonovsky and Bhushan taken into consideration the global impact of tribological studies, they scaled up the knowledge from nanotribology to teratribology formulating the twelve principles of sustainable or green tribology [13] for successful and sophisticated design of machine elements.

The performance of engineering systems from a tribological viewpoint is based on two approaches: (a) controlled laboratory experiments/theory and (b) actual evaluation of full-scale systems within industrial case studies. These approaches tend to report different areas of knowledge advancement as the results and procedures are polarised between idealised theoretical approach and the complexity and uncertainty of real life systems. This is particularly apparent for the three different case studies which are examined in this paper and were contributed in the sustainability concept through sustainable tribology. The first study is focused on the durability of the main components of scroll expander systems integrated within domestic micro Combined Heat and Power units (CHP). The second study examines the friction and wear problems, as well as the substitution of harmful lubricants during the RNLI's (Royal National Lifeboat Institution) lifeboat slipway launch process. The last study examines the potential for recycled plastic materials to replace polyurethane used on skateboard wheels, scooters or similar applications. In each case the durability, the performance and the product design of the actual systems were enhanced, providing quantifiable beneficial, financial and environmental outcomes to society and to the industry.

2. Case study A: micro-CHP systems

2.1. Background to research

Micro-generation can play a vital role in reducing the extensive and wasteful use of energy of the domestic sector with a view to improve living conditions and environmental quality by using environmentally conscious technologies. Nowadays, micro-generation technology is widespread and can deliver the most cost-effective energy and carbon savings. Micro-generation encompasses everything from Combined Heat and Power (CHP) units, to roof mounted wind and ducted turbines as well as small solar panels which allow consumers to generate their own heat and electricity. The effective coverage of the domestic sector energy needs, the working efficiency, the energy savings and the potential prospects of these particular systems can be found in the work of Tzanakis [24]. Tzanakis has highlighted the massive energy benefits which can be generated by the extensive use of solar panels and micro-wind turbines in the domestic sector. Even if his research was focused in two very different countries (Heraklion Crete/Greece and Glasgow/UK) from a climatologically conditions point of view, the combined use of these systems was found to be essential in alleviating the potential energy costs in a national level for both countries. Furthermore, the extensive use of micro-generation systems in an urban environment in combination with the world's first climate legislation

(2009) by the UK government to reduce its emissions by 80% by 2050 could constitute the framework for the successor to Kyoto which ends in 2012 [25]. The research for efficiency improvement and performance optimization of micro-generation technologies is the key target for the period up to 2020. This will be achieved by improving durability and embracing sustainable development of the main components of micro-generation technologies. Consequently, tribology plays the most important role in this turning point for seeking more efficient sustainable solutions.

Micro-CHPs are the most cost effective of all micro-generation technologies and are able to efficiently generate electricity and heat simultaneously. CHP systems are a form of distributed generation that use internal or external combustion engines to generate electricity while recovering heat for other uses. The benefit of these technologies is their ability to utilize sustainable fuels which makes them environmentally friendly [26–28]. Additionally the increasing industrialization of highly populous countries, such as China and India is only likely to increase the use of these systems in the medium term. It is therefore imperative to increase the sustainability and durability of these systems thus reducing manufacturing costs and the rate of disposal.

The latest Environmental Accounts 2010 produced by the ONS reveals that “Emissions from the household sector which accounts one fifth of total emissions have increased 5.5% since 1990. There was a small increase in 2008 (0.2%) following three years of falling emissions due to an increase in energy consumed for domestic heating purposes [29]. Within the next 10 years a significant number of households are likely to require their installations to be replaced. Of the 24 million households in the UK, as many as 14–18 million are thought to be suitable for micro-CHP units. There is a massive penetration of these systems to the worldwide market. In 2005 16,000 micro-CHP units were sold. Japan accounts for around 77% of these sales followed by the German market contributes 17% while UK market was only contributed to 3%. The value of these markets is estimated to be €135 million. In 2009 annual sales were about 20,930 units market with an estimated market value of €269 million [30]. On top of that companies like Energetix which intents to install 30,000 units the next couple of years in Holland and Austria, are ready to inject thousands of micro-CHP systems to global market [31]. The overall market environment worldwide for micro-CHP is very favourable. In UK, government support together with gas utility action and investment, is leading to strong micro-CHP growth. The UK needs to reach the 20% EU energy saving objective by 2020 and to dramatically reduce damaging carbon emissions by 2050 [32].

The main aspect of sustainability is timeliness. A green strategy must rely on the sustainable development of the residential and industrial sources which contribute so significantly to the greenhouse effect on a daily basis. Harrison [33, p. 1] states: ‘CHP has been identified by the UK government as a key component of its CO_2 abatement program and it also represents the most significant individual measure in achieving the European Union’s CO_2 reduction targets (150 Mt of a total of 800 Mt). In order to meet their CO_2 emission reduction targets agreed at Kyoto, the EU aims to double the proportion of power generated by CHP to an 18% on the total capacity. CHP systems can provide cost savings for industrial and commercial users and substantial emissions reductions’ [33]. Additionally Harrison [33, p. 4] states ‘Micro-CHP systems have the potential to reduce a typical household’s annual CO_2 emissions by between 1.7 tonnes and 9 tonnes. Based on the anticipated ultimate levels of market penetration, this could represent a CO_2 emission reduction of as much as 60 million tonnes annually for the UK’ [33]. Thus on the one hand an extensive penetration of CHP systems, from a global perspective, is already essential. On the other hand their durability and sustainability may be greatly improved so to most fully fulfil their initial environmental concept. The target of this research was to join these two concepts to ensure longer term sustainability becomes reality.

Scroll expanders are commonly the main component of micro-CHPs and are also widely used in the refrigeration industry [34], hi-tech industrial processes and air-conditioning in homes and cars [35] as well as in fuel cell systems [36] and in solar power plants [37]. The increased usage presents many challenges to the environment. The process of manufacture, the efficiency in use, the lifespan of the system and the disposal of the substances, such as refrigerant, used for the operation of the scroll; all have environmental impact. The durability improvement of these systems can significantly reduce indirectly the level of greenhouse gases in the atmosphere, since the system’s efficiency will be enhanced and the amount of the after-system-usage wastes will be drastically reduced. Considering the fact that scroll expander CHP systems, including the air conditioning scroll expander systems, have a mass-market appeal nowadays, their lifecycle extension is thought to be more essential than ever. The specific research contrasts the majority of other studies who focus on performance and efficiency improvements of the scroll expander and the associated influence on the system [38–42]. This current project considers the tribological aspects of the scroll’s critical components during its operational period and investigates the importance of tribology issues, such as friction, wear and cavitation erosion within a context of environmental impacts and system costs throughout the lifecycle [43]. The project enhanced the product design investigating the durability of the scroll device, providing beneficial outcomes and financial and future environmental prospects, to the society and to the companies which are involved with the production and the use of scroll expander systems and micro-CHP units.

2.2. The micro-CHP unit

The experimental domestic micro-CHP system used for this project is illustrated in Fig. 1. The micro-CHP system consists of a small fluid pump, a scroll expander unit, a pressure relief valve, a filter drier, two heat exchangers and an evaporator. The first heat exchanger is directly connected to the boiler unit and heats up the working fluid as it passes through tubes before entering the scroll. The second heat exchanger plays the role of the condenser, condensing the working fluid transferring the heat to the central heating circuit of the house which provides space heating and hot water. The scroll expander turns a generator to produce electricity. The micro-CHP system as an integrated domestic boiler has an efficiency of about 88–90% overall which approximates to a 10% electrical efficiency and an overall heat to power ratio of about 9:1. The system produces 9 kWt (kilowatt of Thermal Power) and 1.1 kWe (kilowatt of Electric Power) per hour consuming 1.2 m^3/h of natural gas in the boiler unit. The system’s working fluid is a high molecular organic fluid while the whole process is based on the Organic Rankine Cycle (ORC).

The scroll expander the main component of the micro-CHP unit, experiences wear, friction and cavitation damage while the lubricant which protects the components of the scroll from excessive wear experiences degradation in due process. Excessive wear and cavitation can increase leakage points across the steel plate leading the scroll expander to an efficiency drop.

2.3. Tribological considerations

The design requirements of the scrolls are very strict [39] and an effort to change them could be lead to a poor performance by the scroll and consequently by the overall micro-CHP unit. Thus, tribology plays a major role in optimising the materials performance and durability while significant changes in the geometrical profile of the scroll are restricted.

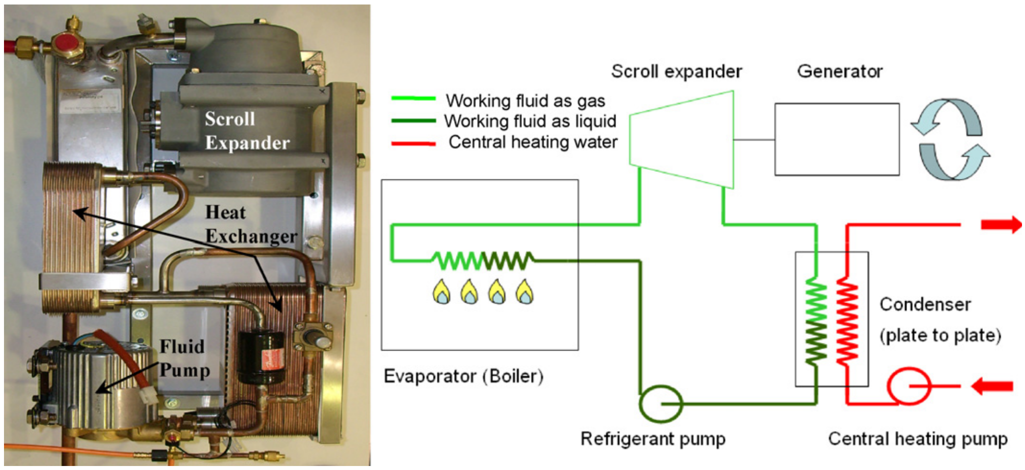


Fig. 1. The experimental micro-CHP unit.

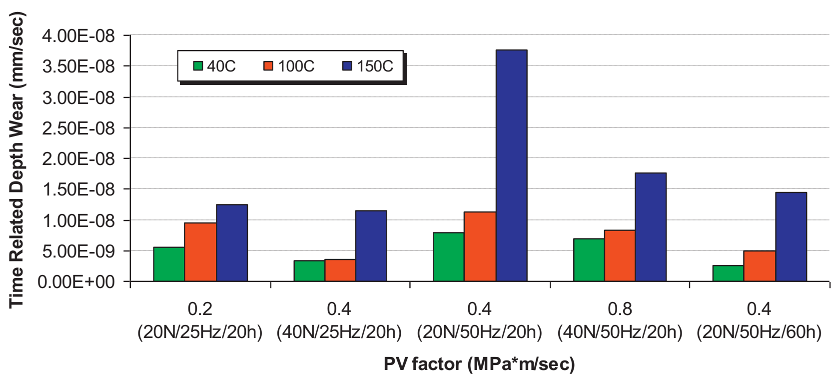


Fig. 2. Variation of the time-related depth wear as a function of the PV factor for various temperature and time sliding regimes [44].

2.3.1. Sliding wear

Tzanakis [44] using a sliding wear test rig and the actual materials of the scroll expander, replicated the conditions within the scroll and performed lubricated friction wear tests. Results were revealed that the friction coefficient and wear rates were strongly dependent on the sliding velocity, contact load, lubricant temperature, and duration of the test (Fig. 2). A combined performance of the above parameters can play a crucial role improving the durability and enhancing the life cycle of the scroll system. Additionally, pressure × velocity factor (PV) showed that an increment of the contact load can substantially enhance the performance of the scroll, lowering the wear rates and simultaneously reducing the radial leakage paths due to the adhesion product formation. The sealing performance of the scroll was improved.

2.3.2. Cavitation

Preliminary investigation of a scroll expander after the end of its service period (1000 h) showed that cavitation dominates the suction area of the scroll [43,45]. Cluster of cavities identified across the surface of the steel plate were analysed and evaluated. The suction area is very important to be maintained for the smooth operation of the scroll. The reason is that in the suction area the pressure drop is inevitable [46] thus any further pressure drop due to cavitation erosion can prove catastrophic for the efficiency of the scroll system.

Research is focused on that critical area in order the responsible cavitation mechanism for the erosion of the scroll's steel plate to be identified [45]. Simultaneously investigation on the dynamic behaviour of the cavitation bubbles of the working fluids of the scroll expander is also conducted [47]. Research findings highlight the refrigerant as the responsible working fluid for cavitation within the scroll, determine the impact pressure of the cavitation bubbles and monitored the evolution of the incubation pits into large eroded craters in due time [48,49]. According to these studies, Figs. 3 and 4 show the depth of the cavitation pits within various fluid environments related to the mean depth erosion within steel materials. Cavitation erosion can rapidly be increased, especially after the formation of cracks across the scroll's steel plate up

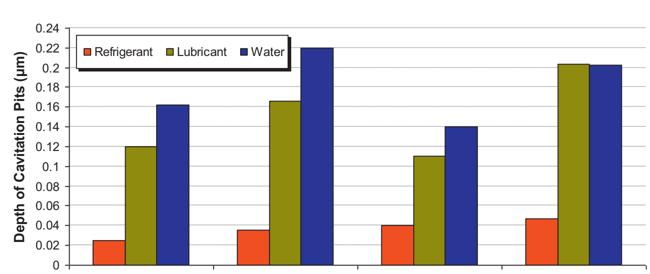


Fig. 3. Comparison of the tested steels according the depth of the cavitation pits within three different liquid environments [48].

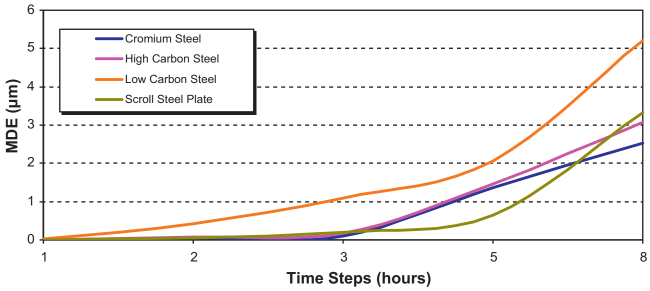


Fig. 4. Comparison of the tested steels according the mean depth erosion (MDE) of the cavitation areas within water environment over different time periods [49].

to 1 μm average depth as studies revealed. Apparently, cavitation becomes more aggressive striking these weak areas and accelerating the erosive wear rates. Thus the cavitation resistance of the scroll can be significantly increased by replacing the damaged steel plate with chromium steel. The chromium steel was found to be 24% more durable and tougher than the steel plate during the 1 h and after 8 h of testing [49]. Thus, chromium steel will initially delay the formation of the cavities minimizing the erosion damage while after a prolonged period of time it would prevent any steep increment of the erosion rates. Hence, the lifecycle of the scroll and simultaneously of the micro-CHPs system can be significantly enhanced.

2.3.3. *Oil assessment*

Three different oil samples after 100 h of sliding tests, using the main components of the scroll expander, removed from the sliding micro-friction test rig and were investigated. The samples were distinguished according to their temperature operating regime at 40 °C, 100 °C and 150 °C, respectively. Temperatures are correlated to the testing regime of the actual scroll [44]. Oil analysis is mainly focused on the wear debris and their contaminants in order to assist in understanding the degradation and the failure mechanisms of the steel/elastomer contact. The oil analysis revealed the condition of the oil samples and the interaction debris responsible for the wear damage. The presence of ferrous and silicon debris within the lubricant solutions after the completion of the tests, justifies that wear damage derived from severe two- and three-body abrasion wear. Interestingly, the 150 °C oil sample found that due to oil degradation replacement oil may subsequently be needed after a short period of time. Under these conditions the lubricant seems to be degraded with loss of its stability and its overall performance. Additionally during the sliding contact flash temperatures are generated which are considerably in excess of the bulk and the average temperature of the apparent contact area. This rise of the surface temperature up to 900 °C can influence the surface geometry leading to severe local wear and lubrication breakdown [50]. It is well known that different loads and speeds in correlation with the higher temperatures in a lubricating system increase the rate of oxidation which automatically determines the level of the lubricant's degradation [51]. This can be proved critical for the operation and the efficiency of the scroll expander. A regular inspection of the oil performance within the scroll is required.

2.4. *Impact and tribological recommendations*

Tribological studies showed that frictional losses, sliding wear, cavitation and oil degradation are the critical damage mechanisms of the scroll expander which can seriously affect the performance and the lifespan of the scroll and consequently of the micro-CHP unit. A number of recommendations provided to industry after the completion of the research project in order the durability and sustainability of the scroll to be improved. These were successfully adapted by industry and applied to their new generation scroll expander systems alleviating any undesirable effects.

2.4.1. *Research impact*

Alterations of the scroll's expander profile improved its performance. An optimization of the shape and the design of the inlet port is achieved by diverting the nozzle. A change in the angle of the nozzle misaligned the direction of the jet stream alleviating high impacts. Additionally with an increment of the height of the spiral walls (increased from 1.5 cm to 3 cm) the elevated impact pressure by the jet stream is significantly reduced by more than 50% as it reaches the upper boundary wall [45] and expands. Consequently cavitation phenomena are restricted. Moreover the lifetime of the main components of the scroll experienced cavitation can be replaced by chromium steel improving the durability of the unit. Chromium steel is found to be 24% more durable and tougher among three other similar steel materials including the actual steel plate of the scroll expander [48,49].

Furthermore, an increment of the applied load between the scrolls can significantly reduce the friction and wear rates while it directly improves the sealing mechanisms by excessive adhesion. The contact pressure between the scrolls showed that an increment from the initial contact pressure of 0.4–0.8 MPa or even to 0.16 MPa would be beneficial for the operation of the scroll [44]. The leakage points are minimized and the tendency of the working fluid to flow through these areas is further confined. The adhesion performance in combination with the use of a less viscous lubricant (proposed by the researcher to the company sponsor) is proved to be useful increasing the performance and durability of the scroll unit.

2.4.2. *Industrial impact*

Industry considered all the tribological mechanisms which can significantly affect the smooth operation of the unit and adapted the recommendations proposed by the researcher for the next generation of scroll expanders systems. The improvement of scroll's efficiency and durability concurrently improves the sustainability of micro-CHP, meeting all residential needs, enabling significant reductions in both energy bills and carbon emissions. This in turn causes a huge impact in certain areas of society like economy, environment and society itself.

Fig. 5 highlights the impact the tribological optimization and the design of the scroll unit has to different aspects of society. Substantial cost reduction of the unit due to lower maintenance costs will be achieved, most of the critical components and materials due to durability improvement will be preserved, considerable amounts of energy due to the optimization of the friction regime and the sustainability of the scroll will be saved, significant environmental benefits from the extensive use of micro-CHP systems and the restriction of their disposal rate will be delivered and finally the quality of the micro-CHP unit will be enhanced. The material and energy losses reviewed on the basis of a single scroll system or a micro-CHP unit are small. However, taking into account that in the world market well known established companies such as VW (Volkswagen), Mitsubishi, Honda, Hitachi, use similar scroll systems in a large range of their products, when the same loss is repeated on perhaps a million machines of a similar type, then losses become significant affecting the global environmental sustainability while the actual costs become very large [52].

2.4.2.1. *Energy impact.* The energy impact of the specific micro-CHP system is significant. The energy savings after that tribological optimization of the scroll unit could be even higher and the payback period shorter than the average annual energy savings of £150 per year, which provides a payback of 3–5 years [53]. Through a more sophisticated tribological design the system will

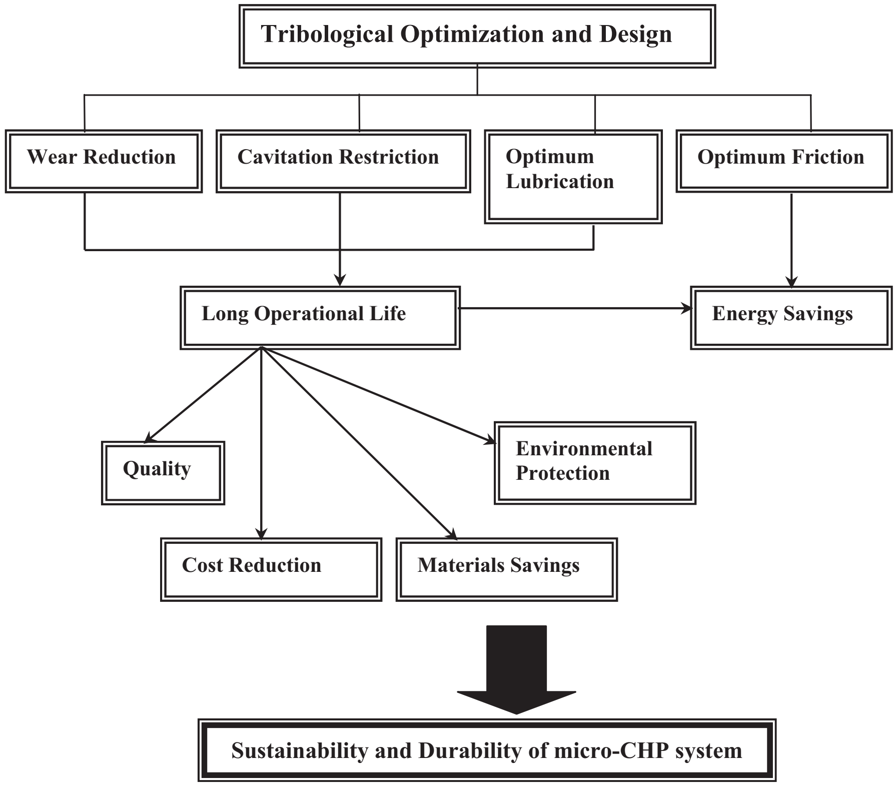


Fig. 5. Schematic representation of the tribological optimization of the scroll expander.

increase its durability (restricting cavitation and wear phenomena), without risking for excessive energy losses due to leakage or extensive friction. This will enable the unit to perform in high energy standards for most of its lifespan period.

2.4.2.2. Economic impact. Economics is a major consideration because products are selected on a cost-use basis. With the tribological optimization of the system, the sustainability of the unit is enhanced minimizing maintenance costs. This in turn will benefit customers alleviating electrical and thermal energy costs. Additionally, the manufacturing process can be improved and lower cost materials with significant better mechanical properties (like chromium steel) can possibly replace the existing ones reducing the overall cost of the scroll unit and increasing its durability.

2.4.2.3. Environmental impact. The studied micro-CHP system saves about 1.5 tonnes of carbon emissions annually [53]. Improving the design and the tribological performance of the scroll the efficiency of the unit will be further enhanced while the fuel consumption will be minimised. Additionally, by enhancing durability of the scroll its operational life will be extended while the disposal rate of substances like refrigerants and lubricants will be reduced.

2.4.2.4. Social impact. The actual micro-CHP unit is a clever environmental friendly system which can be installed in residential houses providing energy, economic and environmental benefits to customers and hence a better quality of life in general to the society. The transition to a green economy represents a substantial challenge to society, particularly in the current era of rapid environmental and socio-economic changes. Society has to comprehend the importance of the green concept, to realise the benefits from the wide use of micro-generation systems and to adapt quickly the potential environmental changes.

In general, key drivers alleviating social and environmental impact include the need to reduce carbon emissions, to reduce the risk of climate change, overexploitation of resources and widespread environmental degradation, which is eroding the natural capital on which human well being depends [54]. Through tribological studies, an optimization of an engineering system improves sustainability; however tribology only with an effective synthesis of all the abovementioned impact parameters can stand out as a coherent and self sustained field of science which will have as ultimate target how to positively impact the green concept of our era. Thus, a creditable impact, like the impact from micro-CHP technologies which it can be massive in a wide range of use, is a key driver to fight against climate change and to improve life quality.

3. Case study B: slipways

3.1. Background to research

Lifeboats have provided a search and rescue service for the British public at sea since 1771. These lifeboats are run by the National Lifeboat Institution (RNLI), a charity, since 1824 [55]. RNLI provides search and rescue cover with 126 all weather lifeboat stations along the coast of the UK and Ireland [56]. In order to do this effectively it is necessary to place lifeboat stations in locations where there is no natural harbour to provide shelter, in this situation the lifeboat is held in a boathouse above the water and released into the sea by means of an inclined slipway (Fig. 6). The lifeboat is held in the raised boathouse until needed and when released slides on its keel along the inclined slipway into the sea.

As the size, the materials and mass of lifeboats have increased over the years [57] however problems of high friction between lifeboat keel and slipway lining have been observed, particularly during the recovery phase where the boat is hauled up the slipway by the recovery winch [58–64]. The high friction between lifeboat



Fig. 6. The launch process of RNLI lifeboat from a slipway station.

keel and slipway has resulted in high winch loads and difficulties in successfully recovering the lifeboat. Thus the design of lifeboat slipway stations has had to be continuously upgraded, the introduction of the new 35+ tonne Tamar class lifeboat in 2005 has required many slipway stations to be significantly rebuilt to accommodate it. Traditionally the friction between the lifeboat keel and the slipway channel has been kept low by manually applying marine grease to the slipway – however, as lifeboat mass and environmental awareness have increased this manual application and repeated uncontrolled release of grease into the local environment, polluting the sea, had become unsuitable, and a new low friction solution was required. The panels are also expensive and it is estimated that at current wear rates the cost of replacing worn composite slipway panels is likely to be in the region of £5k per week once he process of upgrading slipway linings at stations across the UK is complete [65]. This translates as £260k per year which is a significant drain on the RNLI's resources, particularly as it is entirely funded by charitable donations.

The RNLI approached Bournemouth University in 2004 to help to investigate a potential solution to this problem, at this time a number of low friction alternative slipway lining materials had been trialled, with a jute/phenolic resin composite featuring embedded graphite to reduce friction as the main slipway lining material in use. The Jute/phenolic composite was originally intended to be run without lubrication – however the friction encountered in this case was too high and individual slipway stations soon returned to the practice of manually applying grease along the slipway. Additionally the Jute/Phenolic panels were observed to be wearing heavily, in some cases needing replacement within weeks rather than the 2 year plus design life intended – this also placed significant strain on the RNLI financially.

The slipway launch situation provides an interesting contact situation with a heavy 35 tonne lifeboat resting on a 15 cm wide keel in sliding contact with the slipway lining material while the lifeboat speed at the base of the slipway can be over 40 kph. Consequently, the contact can be characterised as high pressure and high velocity. Additionally RNLI equipment usage is typically unpredictable, low frequency and high impact in nature with system reliability critical to saving lives. The current RNLI maintenance system is based on set intervals between inspections. Due to the unpredictable and varied nature of the system usage, this involves unnecessary equipment down-time or conversely insufficient maintenance depending on the severity of the operations. The RNLI research case study worked towards the maintenance based on systematic recording of the actual equipment condition, identifying wear and maintenance issues as, and when they occur. Moreover the project encompassed product design and the use of materials while was very beneficial to the RNLI particularly to sliding friction and wear modelling. This approach had many economic and environmental benefits to RNLI and to marine industry in general, enhancing the overall machine reliability.

3.2. Slipway surveys

The experimental results at this stage were inconclusive, and further work in the form of a detailed panel alignment survey along a number of lifeboat launch slipways was necessary to explain the high panel failure rates found. In this way, four basic types of wear were defined: Panel cracking end wear, Gouging wear, Plane abrasive wear and Delamination wear. It was seen however that the abrasive panel end wear was by far the most common form of wear observed, and that this coincided with significant panel misalignments at the panel interface.

Detailed panel alignment surveys were conducted at Padstow and Tenby to assess the degree of panel misalignments present along the slipway, these surveys found panel steps up to 4 mm were present with an average step of 0.816 mm. The compressive strain at failure for the slipway lining composite used on these slipways is listed in the manufacturer's literature as 1.9%, for a 19 mm thick slipway panel this means that the material will deflect up to 0.361 mm before compressive failure which indicates that that panel compression under load will not be able to accommodate the misalignments.

3.3. Tribological considerations

3.3.1. Friction/wear results

One of the first results from the initial reciprocating tribometers showed that the dry sliding friction between the keel and the slipway panels was too high and that a lubricant was necessary [66–68]. This result also raised questions about the suitability of the slipway panel material as the embedded graphite will only have a mitigating effect of friction under dry sliding conditions. The reciprocating tribometers results showed that all the lubricants tested were able to reduce the friction to below the design specification of $\mu = 0.167$ in order to allow the lifeboat to move under its own weight on a 1 in 6 slipway (Fig. 7). However, the use of freshwater and seawater lubrication – by now, the preferred solution, was shown to be very close to this design limit.

The rotary tribometer results were used to calculate the wear rates of the slipway lining composite under varying lubricant regimes. The wear was shown to be uniformly low, far too low to explain the high panel failure rates encountered whichever lubricant was tested [69].

3.3.2. Finite element models

The friction, wear and panel misalignment data were now combined using a finite element (FE) model to assess the likely real

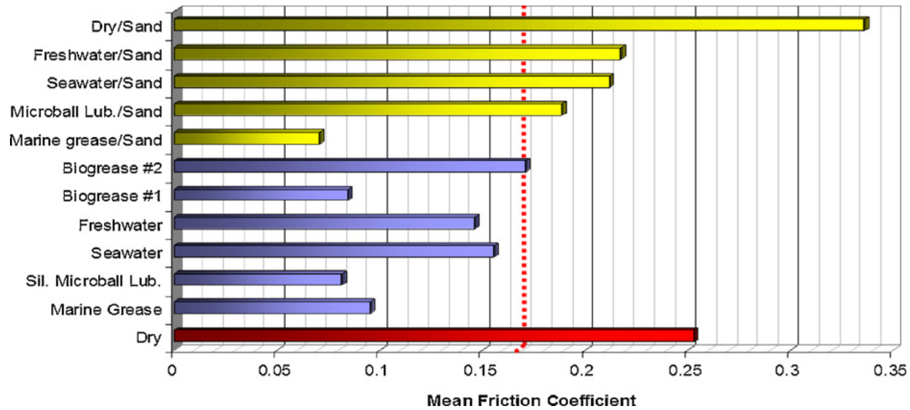


Fig. 7. Composite friction coefficient vs. lubricant regime 10 h Test [69].

world implications of the contact scenario. Here, it was found that the panel misalignments observed during the slipway surveys could have a very serious impact on the contact stresses, and consequently the friction and wear on the slipway [70]. To counter this, a solution involving fitting a chamfer to the slipway panels was proposed. This new design removed much of the stress concentrations associated with slipway panel misalignment, especially in the most common parallel panel misalignment scenario.

3.4. Research summary

The modifications suggested by the finite element (FE) models, slipway surveys and experimental data are sufficient to allow reliable water lubricated slipway operation. The removal of grease from the open marine environment in this case has great environmental benefit, and, coupled with the lower panel failure rates using the modified slipway panel, also presents significant cost savings to the RNLI (Fig. 8).

Combining the costs of marine grease lubrication and panel replacement gives a current annual operating cost of £312k, switching to chamfered slipway panels and a water based lubrication system will reduce this to £117k per year, a saving of £195k.

3.5. Implications for slipway lubricant practice

The tribological tests indicate that under good contact conditions the composite lining is only able to reliably exceed the friction specifications if a lubricant is used. All lubricants tested were able to reduce the friction coefficient to below this level. Wear results were seen to be uniformly low under ideal conditions for all lubricants tested, even when contaminated with sand. Wear is seen to be a problem along real world slipways however, and the FE analysis details the effects of the contact moving away from the perfectly aligned plane sliding case which would seem to account for much of the wear exhibited by real world slipways rather than the choice of lubricants.

With all lubricants tested performing up to the required friction standard selection criteria and wear determined to be more dependant on panel alignment than lubricants used, selection is now based on safety and sustainability factors. When considering sustainability aspects and the dangers of manual application of grease to the slipway which in part prompted this research, the lubrication regimes of freshwater and seawater are proposed, as these are the only lubricants that can be applied to the slipway without manual aid. Of the two, seawater has the slightly lower environmental impact, thought the impacts of both are low and practical considerations should take precedence when choosing between the two. The use of greases or other lubricants manually applied to the slipway is shown to be unnecessary here as freshwater or seawater lubrication performs sufficiently well. Manually applied slipway lubricants are shown to function well at reducing friction coefficients, but doubts are expressed as to the environmental impact of using some of these long term.

(1) Microball lubricant is considered to be particularly unsuitable as it contains silicon ‘microspheres’ these were shown to accumulate into a hard mass during testing and it is felt that the accumulation of these microspheres could affect the friction reliability of the slipway as well as the local environment.
(2) Marine grease also shows excellent friction characteristics but the guidelines for use imply that it is not particularly suitable for open water use and the low biodegradability means that there is an increased chance of bioaccumulation.
(3) The biogreases tested are shown to perform well, with biogrease in particular exceeding the performance of the marine grease currently used. This suggests the possibility of direct substitution with the marine grease, with the greater biodegradability of biogrease reducing the overall environmental impact in this way.
(4) Freshwater and seawater lubrication are shown to be effective here and the manner of their use addresses the safety problems associated with manually applying grease to the length of the slipway. An added benefit of using running water along the slipway is that this will help to clear the slipway of debris, reducing the friction and wear effects of 3rd body abrasion.

Following this research it is recommended that freshwater or seawater lubrication is adopted for all slipways. In isolated incidences of high friction along the slipway the use of marine biogrease, in a similar manner to existing marine grease application procedures is recommended, however, this should only be used in isolated incidents, if high friction consistently persists along the slipway consideration should be given to slipway panel inspection for wear and misalignment.

3.6. Research impact

The data collected indicated that the reliability of lifeboat slipways could be greatly increased by ensuring the slipway panels were well aligned along the length of the slipway. It also showed that a small change to the panel geometry to incorporate a chamfer significantly reduced wear development and the adverse effects of panel misalignments on launch and recovery friction. The project showed that it was feasible to substitute the currently used marine grease lubrication with biodegradable greases, reducing the effects of grease bioaccumulation at the base of the slipway. The research

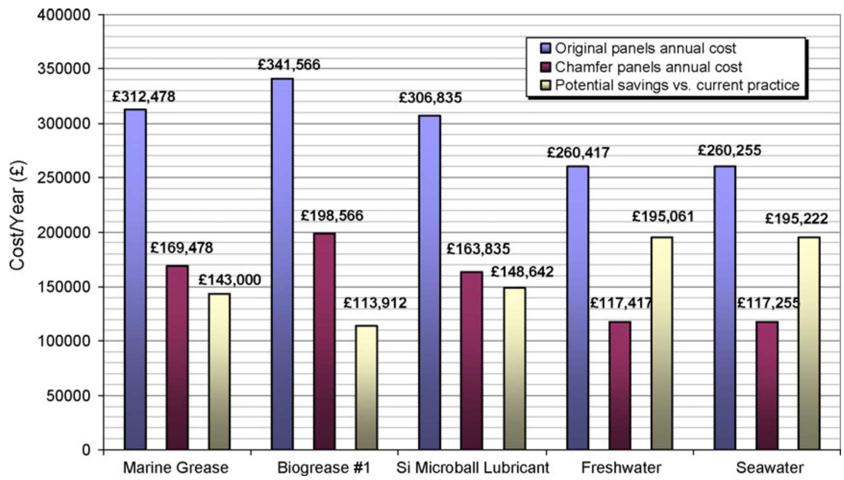


Fig. 8. Slipway operating costs/year – original panel vs. chamfer panel [70].

also proposed the use of a novel water lubrication system involving the manual application of grease to the slipway by lifeboat crewmen is replaced by automatic water based system reducing the cost and environmental impact of lifeboat slipway launches. These water lubricated systems have subsequently begun to be adopted across the RNLI slipway network. RNLI's head of engineering support, states that "the findings of the specific research are extremely valuable to the RNLI as they outline improvements that can be made to produce more efficient, durable and cost-effective slipways from which to launch and recover the lifeboats" [71].

The combined effects of Thomas' research has allowed the RNLI to save up to £200,000 [72] per year in operational costs while at the same time significantly reducing the environmental impact of lifeboat slipway operation and increasing launch reliability. The research also reduces the risk exposure of the volunteer lifeboat crew who crew each slipway station, and allowing the safe continuation the RNLI's crucial role in preserving life along the coast of UK and Ireland. The changes recommended by the research are already underway, the new slipway lining material has been fitted to the newer slipway stations (e.g. Tenby, Padstow, etc.) already and the water lubrication systems are also in place. The recommended slipway lining material and water lubrication systems are being phased in across the remaining UK slipway station network over the next few years, coinciding with the simultaneous rollout of the new Tamar lifeboat to the slipway stations [72]. Additionally the societal impact through out this research considered to be significant. Social benefits include an important contribution to the on-going reliability and security of vital lifesaving services nationally through the reduction in maintenance down-time and machine failure.

4. Case study C: recycled plastics

4.1. Background to research

Skateboard wheels have gone through a huge change since the 1950s, when the first commercial skateboards normally had wheels made of steel which offered a rough ride and little or no traction [73]. Clay wheels, formed from a composite of clay, plastic, walnut shells, paper and polymer binding agents [74], appeared by the 1960s and partially solved the problem of steel wheels. Clay wheels offered a smoother ride, but still lacked the grip needed to prevent riders from getting injured [75]. Furthermore, these wheels lasted only a few hours on hard pavement and were still vulnerable to surface imperfections [73]. It was not until 1973 that the first PU (Polyurethane) wheel purposely designed for the skateboard went into production thanks to Cadillac Wheels in conjunction with the roller skate company Creative Urethanes, and helped turn skateboarding into a popular sport, replacing the existing steel and clay wheels. Each kind of wheel offers different properties, making it more specific for a type of skateboarding than others and allowing skateboarders to ride in any type of surface [74]. All the different kinds of PU are created by a chemical reaction between a diisocyanate and a polyol. Depending on the selected starting materials, (there is a wide range of diisocyanates and polyols that can be combined), the properties of the finished product will vary [76]. PU wheels offered a smoother ride and gripped the road better, making skateboarding safer and increasing its popularity. Moreover, they are very durable and do not lose their shape [73–76], offering high load capacity and abrasion resistance.

Nevertheless, the PU employed is difficult to recycle and with the dwindling resources and environmental problems facing the world today, recycling has become an important aspect of the future sustainable society. Furthermore, the total production of plastic consumption is growing day-by-day and new and stricter laws related to recycling are emerging. One of the main problems with plastic recycling is that, when a plastic is recycled its properties often deteriorate and its mechanical performance decreases, reason why recycled plastics are commonly used in less demanding applications than the original product made of virgin material [77]. Additionally, it is difficult to guarantee material properties for these recycled so designers have to be aware of reduced design limits. Recycled plastics are used in different applications, such as automobiles, household goods, packaging and construction [78] where performance demands are not very high, however these applications cannot fully address the amount of plastic waste generated annually, a need to find new uses for these recycled plastics is required. Nowadays, PU continues to be the material used in the manufacture of skateboard and scooter wheels [79], which are offered in a wide range of options, varying mainly in terms of their hardness, diameter, shape, colour, etc.

The potential application of recycled plastic materials to replace PU used on skateboard and scooter wheels is investigated. After analysing the operational conditions of skateboard wheels, a range of recycled plastics with similar properties to PU are selected. These materials are later tested in sliding and rolling tribological experiments against an asphalt, a concrete and a pavement sample considering test conditions to the real case scenario. The results indicate the friction and wear performance of the recycled plastics in comparison with the corresponding PU samples. Data obtained from the tests show that recycled (PC) Polycarbonate could be a suitable replacement for PU. Moreover, sustainable considerations regarding the use of recycled plastics are analysed,

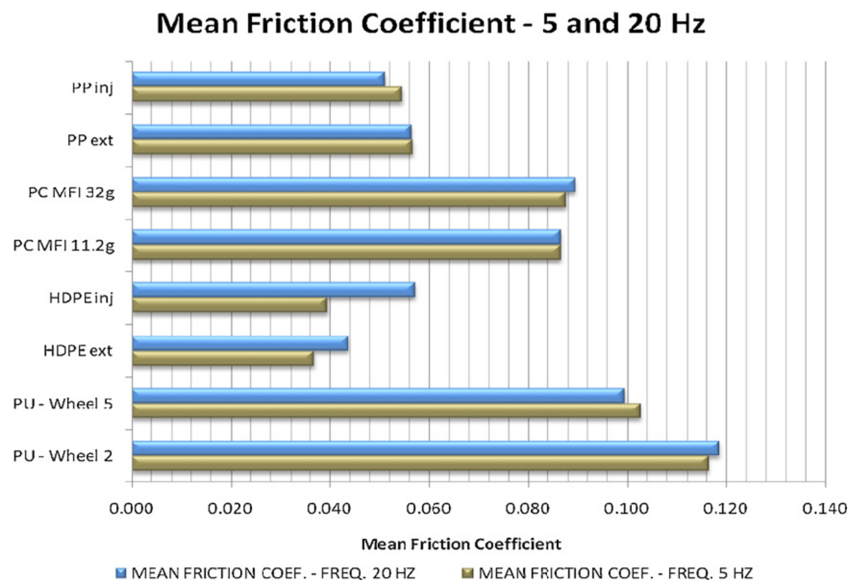


Fig. 9. Mean friction coefficient for all the tested recycled materials at 5 and 20 Hz.

showing the advantages of the use of recycled plastics for the environment including reducing the CO_2 footprint a 50% and the energy consumed a 60%, among other benefits.

4.2. Tribological analysis

All the materials tested show consistent friction coefficient values for the different conditions simulated, with low standard deviation values, proving that the values obtained do not vary significantly (Fig. 9). All of the PC grades tested present friction coefficient values slightly lower than the corresponding PU ones (0.09 for PC versus 0.1–0.15 for PU). The rest of the recycled plastics tested, HDPE (high density Polyethylene) and PP (Polypropylene), show very low friction values that makes them unsuitable for skateboard applications (friction values varying from 0.04 to 0.05). The sliding wear tests carried out, showed that PC presents a better wear factor than PU, indicated by very low material wear losses. As a result of the friction and wear tests conducted, it is shown that PC could be a potential material for replacing PU wheels used on skateboard.

4.3. Sustainable considerations

The increasing increment to the overall amount of plastics recycled every year is imperative. Plastic recycling has many sustainable advantages, including the reduction of the CO_2 footprint, the reduction of the embodied energy consumed and the conservation of oil resources (most plastics are made of crude oil, representing a 4% of the total oil consumption [80]). Additionally, the total amount of waste that goes to landfills and incineration can be significantly reduced by recycling suitable materials. Nowadays, the vast majority of skateboard wheels are produced with non-recycled PU. However with the use of recycled plastics proposed in this study to replace PU products, several environmental benefits as well as a significant reduction in the product cost can be achieved, since the price of the recycled plastics is far lower than that of PU.

With more than 50 million skateboard users worldwide [81], the quantity of wheels manufactured every year by the wheel industries is massive. Skate wheels are also a high turnover product with skaters often upgrading their wheels regularly to keep up with prevailing trends. Assuming that each skateboarder uses one set of wheels per year as an average (one set contains 4 wheels), this means that at least 200 million wheels produced every year. Each set of wheels has an average weight of 0.85 kg thus a total of 42,500 tonnes of PU are used globally every year in skateboard wheel production. Using CES Selector 2010 analysis software, this amount corresponds to 284.75 million kg CO_2/year tonnes of CO_2 emitted each year. This figure does not include the use of similar wheels on scooters, roller-skates, toys, shopping trolleys, etc.

4.3.1. CO_2 footprint

The total CO_2 footprint (Fig. 10) for recycled plastics is calculated as the addition of the CO_2 footprint from recycling and from moulding using appropriate software (CES Selector 2010). The CO_2 footprint from the primary production is not considered, since recycled plastics have been used before in another product and are waste that otherwise would have been sent to a landfill or heated for recovery of energy. In contrast, the total quantity of CO_2 footprint emitted to the atmosphere from PU is calculated as the addition of the primary production and the moulding CO_2 footprints, respectively.

If recycled plastics were used instead of the typical PU plastics in the manufacturing process of skateboard wheels the total CO_2 footprint would be reduced by almost a 50%, since a reduction of 6.7 kg CO_2/kg PU to a mean value of 3.6 kg CO_2/kg recycled plastic (PP, HDPE, PC) is observed. Considering the fact that 42,500 tonnes of PU employed every year, the total CO_2 footprint produced is 284.75 million kg CO_2/year. If this material was replaced by the recycled plastics and the global production remained constant, the CO_2 footprint would have been reduced to 148.75 million kg CO_2/year, therefore saving 136 million kg CO_2/year. According to the average production on a household [82] of 12.4 tonnes/year, the above mentioned savings would correspond to the annual emissions of around 11,000 households. Combining this with the potential annual domestic savings by the use of micro-CHP's (1.5 tonnes/year) the total environmental benefits from the restriction of carbon footprints are massive.

4.3.2. Embodied energy consumption

Following the previous analysis, the total energy consumed in the manufacturing process of a plastic product varies, depends on the primary source: primary plastic or recycled plastic. Fig. 11 shows the energy consumed using CES Selector 2010. Once again, the energy consumed is substantially lower when using recycled

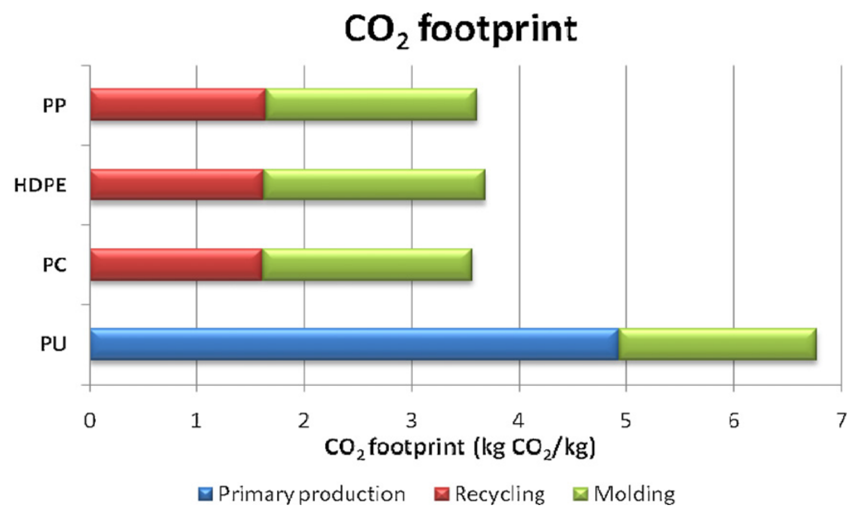


Fig. 10. Evaluation of CO_2 footprint for various recyclable polymer materials.

Table 1
Costs of different plastics materials for the year 2011. Annual costs and savings.

Material	Price (£/kg)	Total price (millions of £/year)
PU	3.3	140.3
PC	1.1	46.8
HDPE	0.44	18.7
PP	0.5	21.25

plastics, proving sustainability improvements as the energy consumed for the production of one kg of recycled plastics corresponds to just 60% of that consumed for the same weight of PU. Considering the 42,500 tonnes/year PU production, this would mean reducing the total energy consumption by 2200×10^6 MJ/year (5510×10^6 MJ/year for PU compared to 3310×10^6 MJ/year for the recycled plastics PP, HDPE, PC).

4.3.3. Economic analysis

Sustainability includes wider issues such as economic and social aspects, which combined with the environmental impacts represent the 'three pillars' of sustainability. The cost of PU is substantially more expensive than that of the recycled plastics, especially the price for HDPE and PP, which can be up to 10 times smaller (Table 1), representing annual savings between £93.5 and £121.6 million per year, depending on the material used.

4.4. Research impact

PC is shown to be a potential material for replacing PU wheels used on skateboard. Using recycled PC in the manufacture of skateboard wheels could potentially save more than £90 million pounds globally every year, reduce the CO_2 footprint by 136 million kg CO_2/year as well as cutting energy consumption by 60%. Furthermore, the total amount of plastics going to landfills every year would be reduced, not only because of the 42,500 tonnes of PU that would not be produced every year for wheels, also because of the other 42,500 tonnes of PC (or any other recycled plastic used) that could be taken out of landfills, which would make a total of around 85,000 tonnes saved every year.

4.5. Other considerations

Recycled materials could be further integrated into PU-style wheels with the use of so called "dual durometer wheels", which are wheels with an inner core made from a different material to the riding surface. Normally, the inner core is harder than the riding

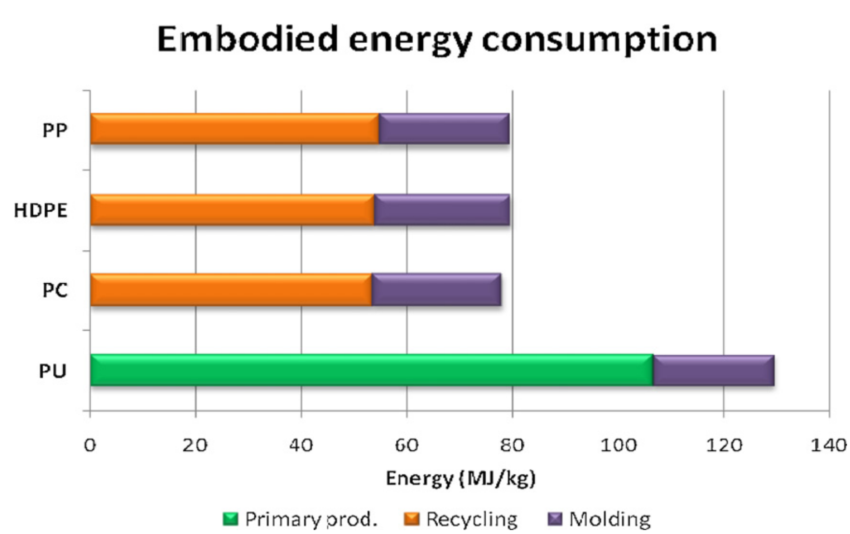


Fig. 11. Evaluation of embodied energy consumption for various recyclable polymer materials.

surface, i.e.: 100 A vs 95 A. This creates less flex on the bearings when doing demand tricks and a more controlled ride while large inner creates a wheel that is about 20% lighter weight than standard. Therefore, the inner core could be made of a recycled material while the riding surface could continue being made of PU, which would mean that the friction and wear rates continue unmodified, but a large quantity of recycled plastics could be used in this application, with all the environmental and economical benefits that this would involve.

5. Discussion

5.1. Tribology and sustainability

Three different case studies investigating the impact of tribology to sustainability were conducted. The studies were focused on the tribological performance of critical systems considering at the same time the energy and environmental benefits and the socio-economical impact. Although the studies derived from different engineering fields (industrial engineering, marine engineering and plastics engineering) their final outcomes have a common denominator, the enhancement of sustainable development through sustainable design, durability and life quality. Research highlighted the appreciation of sustainable thinking through the green tribology concept showing that viability can be achieved leading the world to more sustainable solutions.

Exploitation has a direct and significant impact in the micro-CHP systems industry, while the scroll expander can be transformed to an even more efficient and environmental friendly domestic device. The outcomes from the micro-CHP research study have a serious impact: in the durability and the sustainability of the product through design alterations and material modifications. Wear and cavitation problems were successfully tackled and the lifecycle of the system enhanced. Economic, environmental and social benefits were determined and their impact is revealed. Correspondingly the outcomes from the RNLI research project and the recycled plastics exploitation show similar results. The results from the RNLI project showed that the use of the biogrease and water lubricants can dramatically affect the wear rate of the composite lining material, alleviating wear and friction rates. The specific lubricants are friendly to the marine environment restricting pollution rates. Moreover the use of modified chamfer panels in place of the current panel design is shown to reduce the effects of panel misalignments leading along to reduced wear and friction on slipway panels. Additionally using water lubrication and chamfer slipways panels could potentially save up to nearly £200k per year whilst improving the safety, reliability and panel lifespan of launched lifeboat operation. On the last project the potential for using environmental friendly recycled plastics to replace polyurethane used on skateboard wheels is shown. The sliding wear tests carried out revealed that polycarbonate wear and friction rates are only slightly lower than that of polyurethane, presenting smaller wear losses. Additionally, using recycled polycarbonate in the manufacture of skateboard wheels could potentially save more than £90 million globally every year, reduce the CO_2 footprint by 136 million kg CO_2/year as well as cutting energy consumption by 60%. Interestingly with an effective combination of recycled plastics and micro-CHP's the annual carbon footprints can radically be reduced. Furthermore, the total amount of plastics going to landfills every year would be significantly reduced. The 42,500 tonnes of polyurethane produced for wheels development every year will be constricted while other 42,500 tonnes of polycarbonate would be taken out of landfills, for manufacturing process. Consequently 85,000 tonnes of plastics every year will be potentially saved by the use of recycled plastics.

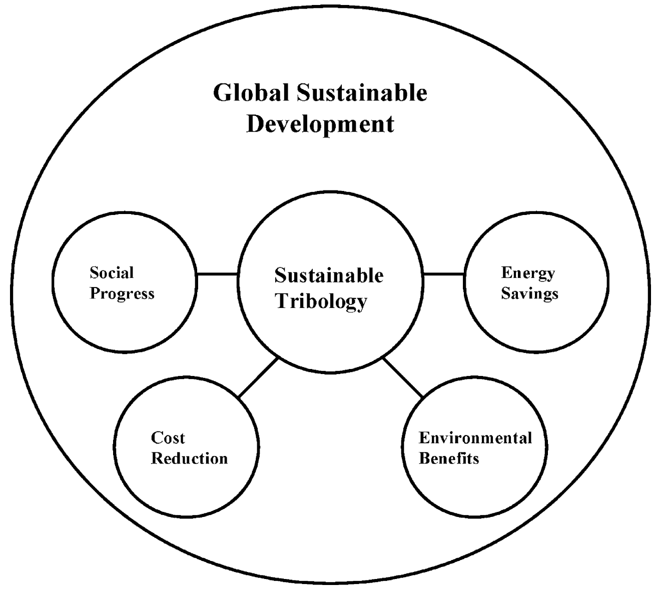


Fig. 12. The impact of sustainable tribology to sustainable development.

In Fig. 12, sustainable tribology highlights the fundamentals aspects of sustainable development by addressing the practical functions of an engineering problem to improve efficiency and durability, by minimizing the cost of a system to benefit the consumers and by reducing material resources and energy consumption to protect the environment. Consequently, through sustainable tribology social progress can be achieved by radically improving people's well being and life quality.

Additionally, taking into consideration the concept of sustainable development which is defined as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [83] and the approach by the United Nations that "The challenge of *energy* for *sustainable development* will require a concerted effort on the part of international organizations, national governments, the energy community, civil society, the private sector, and individuals. Whatever difficulties are associated with taking appropriate action, they are small compare to what is at stake. Because humankind is in a dynamic and critical period of economic, technological, demographic, and structural transition, and because *energy systems* take decades to change, the time to act is *now*" [84] the need to put the world on the path of sustainable development is imperative. Within sustainable development these broad interacting aspects environment, economics, and social equity are addressed by Robinson and Bers saying that: "These three aspects are inseparable and our ability to develop a deeper understanding of this linkage is critical to our prospects for sustainability" [85]. The sustainability of development can be assessed in economic, environmental and social terms however in practise, sustainable development is about finding acceptable trade-offs between economic, environmental and social goals. It is then clear that the *future perspectives of sustainable tribology* are closely related with the environmental stewardship, economic growth and social equity. The control of friction and wear is extremely important for energy conservation and conversion as well as the environmental aspects of lubrication and refrigeration technology. Sustainable tribology in turn develops sustainability across the globe.

In the aforementioned studies, which incorporated a broad range of industrial engineering, the author believes that tribology and sustainable tribology as far as it is found in all the neuralgic sectors of our society (industry, sports, science, space, etc.) and subsequently incorporating social, economic and environmental

dimensions can be characterised as the key driver for sustainable development; reorienting technology, reviving growth, indicating quality, securing viability and mimicking the natural processes. The relation between tribology and sustainability is profound and interactive, embracing sustainable development and design. Tribology improves Sustainability and likewise Sustainability improves Tribology.

6. Conclusions

The three case studies discussed here indicate how the impact that sustainable tribology encompasses to different aspects of society is emphasised through established research and practical examples. The combined outcomes from the case studies indicate the wide ranging and varied contributions that tribology for sustainability can make towards a future sustainable global society. The specific relationship of tribology and sustainability is inextricably linked with the tribological benefits of longer lifespan through lower wear, energy savings through a reduction in frictional losses, the selection of effective environmentally conscious lubricants and the development of alternative bearing materials to reflect the twin pressures of increasing resource scarcity and increasing material waste. These benefits contribute to the wider sustainability issues of economic growth, social progress and environmental protection. Tribology is already integrated into world science, finding solutions to daily worldwide problems, improving global quality, preserving energy resources and protecting the environment, however the specific application of tribology to sustainability issues is a relatively recent trend and the full range of potential applications for this combined approach is only now becoming clear.

Thus, it would be wise to conclude that in our epoch sustainable tribology is more essential than ever, stimulating sustainable development and providing stability to our world embracing an anthropocentric and viable growth to our societies through effective sustainable solutions.

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